

Low Frequency (11 mHz) Oscillations in H1743–322: A New Class of Black Hole QPOs ?

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ABSTRACT

We report the discovery of quasi-periodic oscillations (QPO) at ~ 11 mHz in two RXTE observations and one Chandra observation of the black hole candidate H1743–322. The QPO is observed only at the beginning of the 2010 and 2011 outbursts at similar hard color and intensity, suggestive of an accretion state dependence for the QPO. Although its frequency appears to be correlated with X-ray intensity on timescales of a day, in successive outbursts eight months apart we measure a QPO frequency that differs by less than ≈ 0.0015 Hz while the intensity had changed significantly. We show that this 11 mHz QPO is different from the so-called Type-C QPOs seen in black holes and that the mechanisms that produce the two flavors of variability are most probably independent. We compare the 11 mHz QPO with other variability phenomena seen in accreting black holes and neutron stars and conclude that although at 1-2 orders of magnitude lower in frequency, they best resemble the so-called “1 Hz” QPOs seen in dipping neutron star systems. If confirmed, H1743–322 is the first black hole showing this type of variability. Given the unusual characteristics and the hard-state dependence of the 11 mHz QPO, we speculate that these oscillations might instead be related to the radio jets observed in H1743–322. It remains unexplained, however, why similar QPOs have not yet been identified in other black holes and why they have only been seen in the last two outbursts of H1743–322.

Subject headings: X-rays: binaries — binaries: close — stars: individual (H1743–322) — Black hole physics

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1. Introduction

Low-frequency quasi-periodic oscillations (QPOs) with characteristic frequencies between a mHz and tens of Hz have been observed in the X-ray flux of Low-mass X-ray binaries (LMXBs) containing neutron stars (NSs) and black holes (BHs). The characteristics of these QPOs are known to generally correlate with the source spectral states and/or X-ray luminosity (see, e.g., van der Klis 2006, for a review). A number of QPOs can be present simultaneously, and their frequencies are known to be related to each other (e.g., Wijnands & van der Klis 1999; Belloni et al. 2002). However, there are QPO features which do not clearly fit into these known frequency relationships.

Among the exceptions found in NS systems are; (i) the so-called hecto-Hz QPO, whose frequency is constrained between ~ 100 Hz and ~ 300 Hz (e.g., Altamirano et al. 2008a), (ii) the so-called 1 Hz QPOs in dipping sources (e.g., Jonker et al. 1999, 2000; Homan et al. 2003), (iii) a QPO with frequencies in the mHz range which very likely results from marginally stable nuclear burning of Hydrogen/Helium on the NS surface (e.g., Heger et al. 2007) and (iv) the 1 Hz flaring observed in two accreting millisecond X-ray pulsars when the sources were observed at low-luminosities (e.g. Wijnands 2004; Patruno et al. 2010).

BHs generally show three main type of low-frequency QPOs (Type A, B and C, see, e.g., Casella et al. 2005) and, in a few cases, high-frequency QPOs (with frequencies between 70 Hz and 450 Hz, e.g., van der Klis 2006, for a review). Sometimes observed QPOs could not be identified with either Type A, B or C; in many of these cases it was due to data of low statistical quality or an unusual spectral state of the source. A clear exception is the low-frequency variability, including for example the “heart-beat” QPOs, observed so far only in the BHs GRS 1915+105 (e.g., Belloni et al. 2000) and IGR J17091–3624 (e.g., Altamirano et al. 2011).

Recently, Strohmayer (2011) reported on a *Rossi X-ray Timing Explorer* (RXTE) observation of the 2011 outburst of the black hole candidate (BHC) H1743–322. In addition to the typical Type-C QPO and strong broad-band noise generally seen at the beginning of the outbursts of BH systems, Strohmayer (2011) found an unusual 91 sec QPO which they suggested could be due to a second active source in the 1^o Proportional Counter Array (PCA; Jahoda et al. 2006) field of view (FoV). However, subsequent observations with *SWIFT* and *INTEGRAL* did not show any additional nearby sources. Triggered by the possibility that this 91 sec QPO could be instead intrinsic to H1743–322, we analyzed all the available RXTE and Swift data to search for other instances of similar QPOs. In this Letter we report the discovery of a similar QPO in additional *RXTE* and *Chandra* observations of H1743–322 and discuss the implications of our findings.

H1743–322 was first detected in outburst in 1977 (Kaluzienski & Holt 1977) and then rediscovered by *INTEGRAL* in 2003 (Revnivtsev et al. 2003). Since 2003 several smaller outbursts of H1743–322 have been observed (see Motta et al. 2010, and references therein). From its similarities with the dynamically confirmed BH X-ray binary XTE J1550-564, the source was classified as a BH candidate (McClintock et al. 2009). H1743–22 is at a distance of 8.5 ± 0.8 (Steiner et al. 2011) and, from the evidence of X-ray dipping behavior (Homan & Belloni 2005), the inclination angle of its accretion disc is believed to be relatively high ($> 70^\circ$) to our line of sight. However, no thorough analysis of the dipping behavior has been reported as yet.

2. Observations and data analysis

The BHC H1743–322 was observed with the PCA on-board RXTE for a total of 558 pointed observations, sampling 9 different outbursts which occurred between March 2003 and June 2011. Some of the H1743–322 outbursts were also sampled with the Swift/XRT instrument (Barthelmy et al. 2005); we used all the 52 archival observations to look for mHz QPOs. We also used a 60ksec Chandra observation (id number, 401083), which was contemporaneous with RXTE observation 95368-01-01-00 (see Section 3.1). We extracted events from the 0th and 1st order High Energy Transmission Grating (HETG/ACIS-S) mode data with CIAO 4.3 following standard recipes¹.

2.1. Light curve and HID

We used the 16s time-resolution Standard 2 mode data to calculate X-ray colors. For each of the five PCA detectors (PCUs) we calculate the hard color as the (16.0–20.0 keV)/(2.0–6.0 keV) count rate ratio; the intensity is the count rate in the 2.0–20 keV band. To obtain the count rates in these exact energy ranges, we interpolate linearly between PCU channels. We then perform dead-time corrections, subtract the background contribution in each band using the standard bright source background model for the PCA (V.6.11), and finally obtain colors and intensity for each time interval of 16s. In order to correct for gain changes as well as the differences in effective area between the PCUs (Jahoda et al. 2006), we used the method introduced by Kuulkers et al. (1994, when analyzing EXOSAT² data):

¹<http://exc.harvard.edu/ciao/threads/>

²A European Space Agency X-ray Observatory Satellite

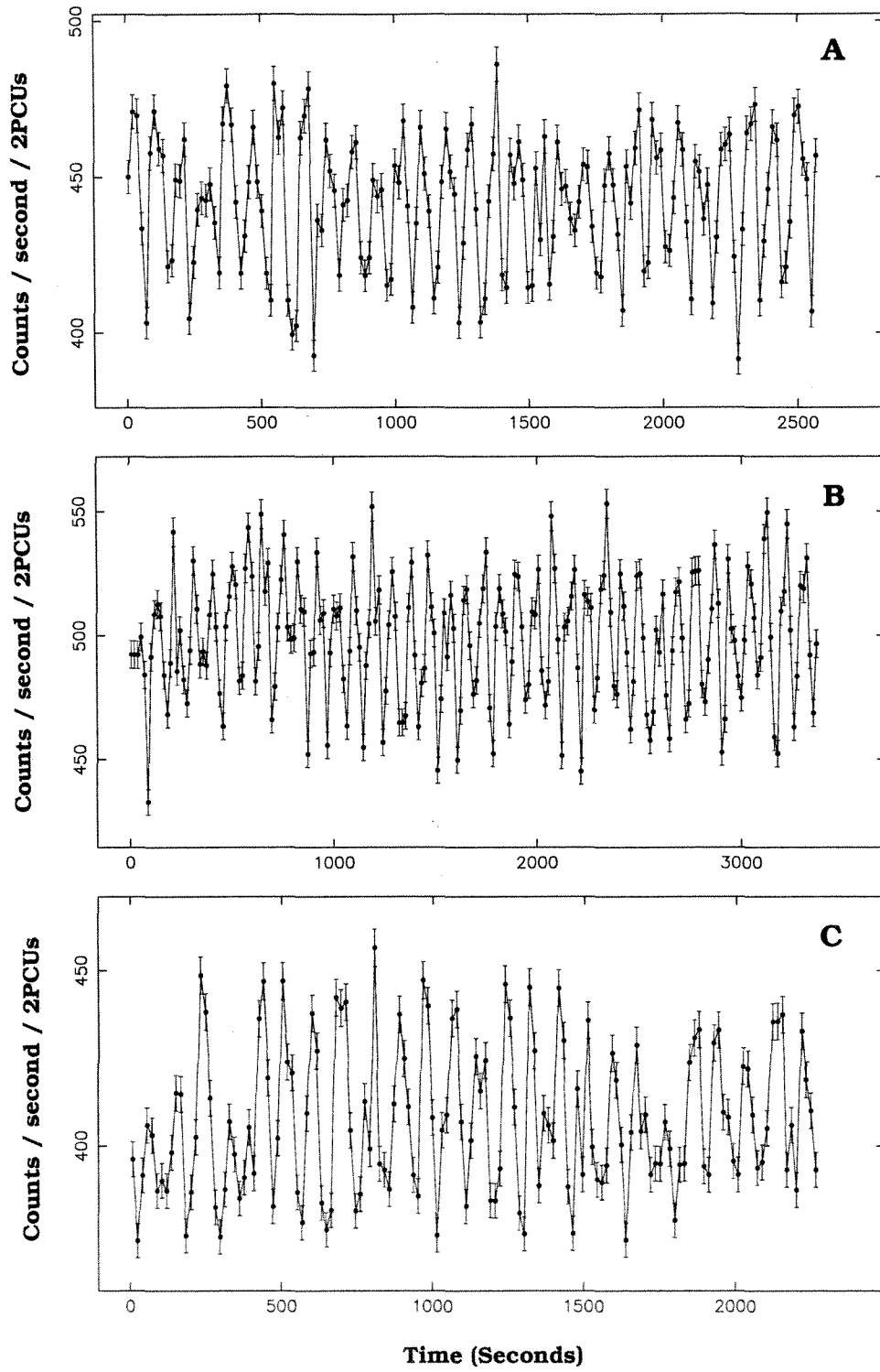


Fig. 1.— 10 s binned RXTE light curves (2–60 keV) of the 3 orbits in which we detect the mHz QPOs. Panels A and B correspond to two orbits in observation 95368-01-01-00. Panel C corresponds to the single orbit observation 96425-01-01-00. In all cases 2 PCUs were active.

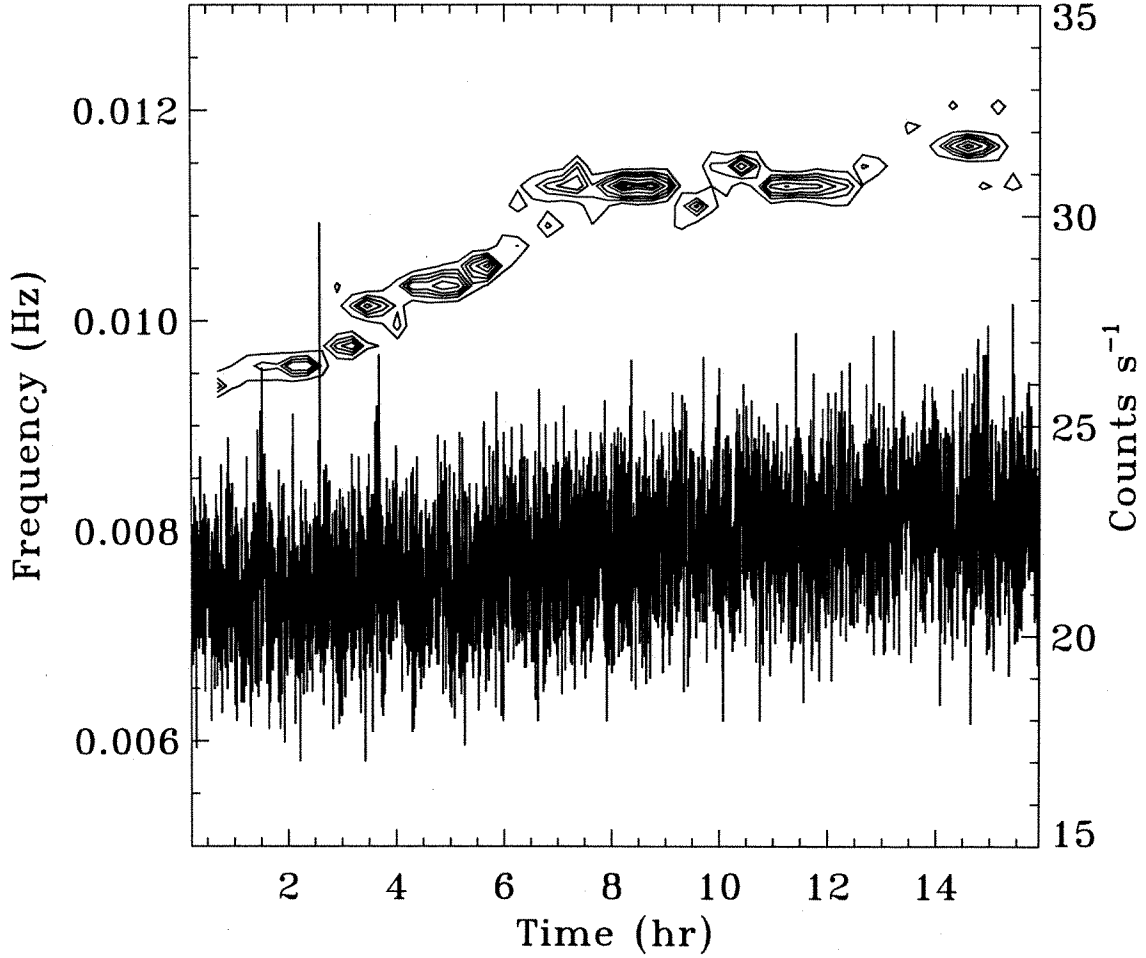


Fig. 2.— Dynamical power spectra from the dispersed (i.e., excluding the zeroth order image) HETG *Chandra* data showing the frequency evolution of the mHz QPO. We computed overlapping power spectra by using 5000 s intervals, with a new interval beginning every 1000 s. Contours of constant Leahy-normalized power are drawn at values of 25, 40, 50, 60, 75, 90, 100 and 110. Start time is August 8th, 2010, 23:03:48UT.

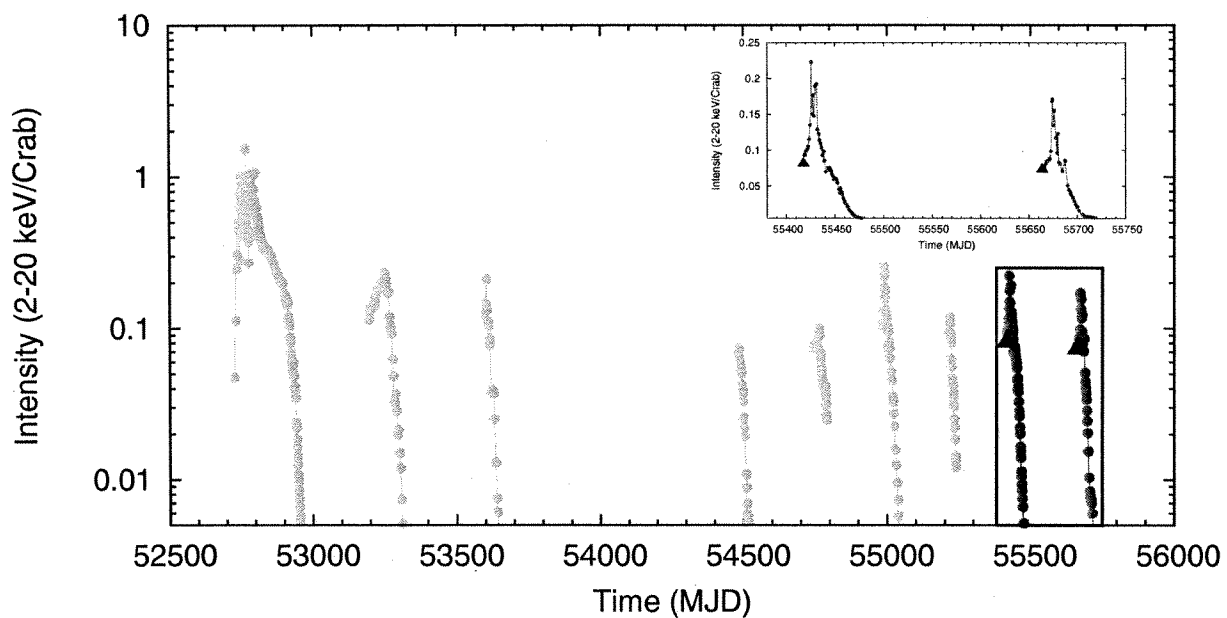


Fig. 3.— Crab-normalized light curves of all outbursts of the BHC H1743–322 as seen with RXTE pointed observations. Each point corresponds to an average per observation. The inset shows the last two outbursts. The triangles mark the times when we detected the mHz QPOs

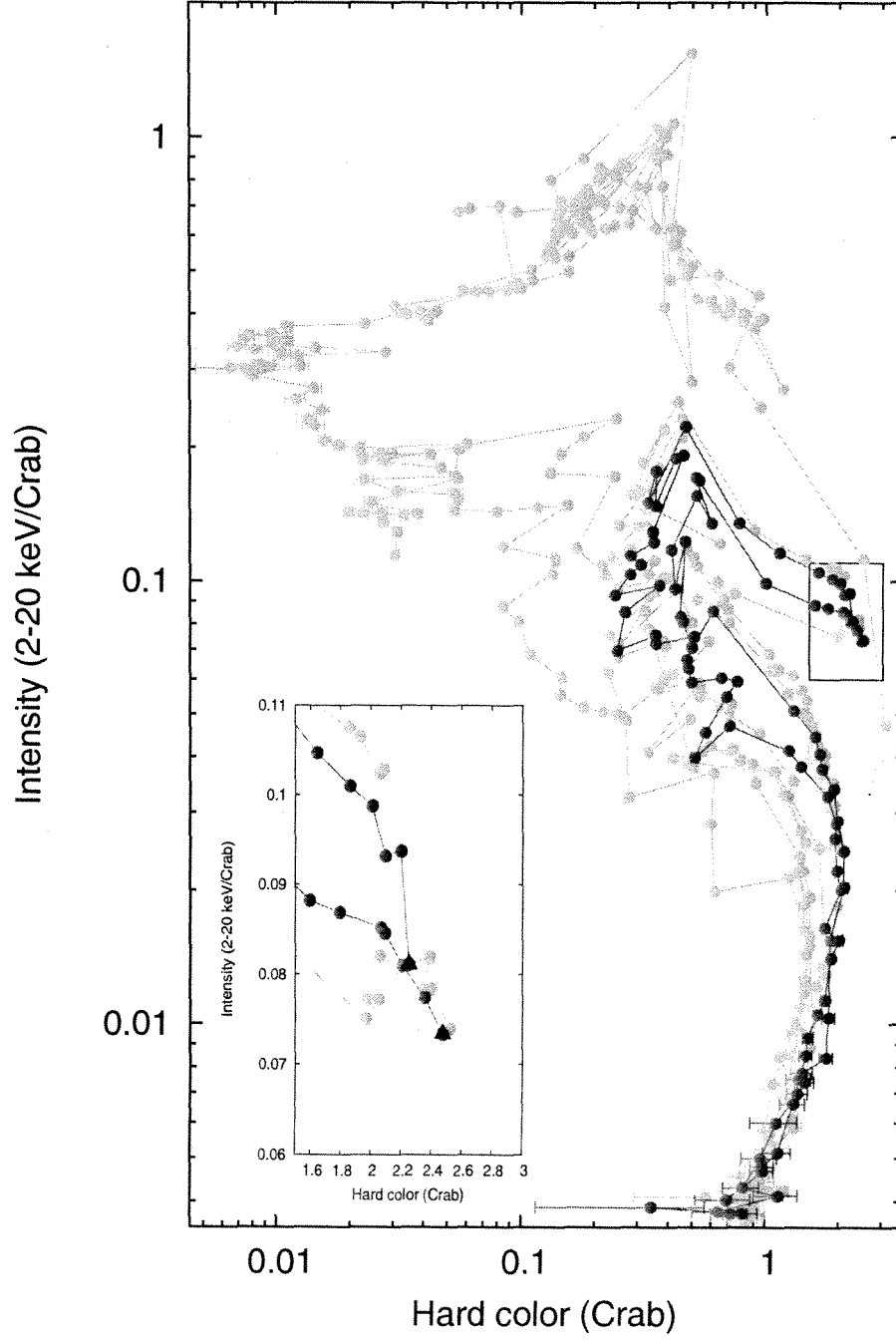


Fig. 4.— Hardness–intensity diagram of all outbursts of the BHC H1743–322 as seen with RXTE pointed observations. Each point corresponds to an average per observation. The inset shows a blow-up of the region in which we detected the mHz QPOs, with triangles denoting the mHz QPO observations.

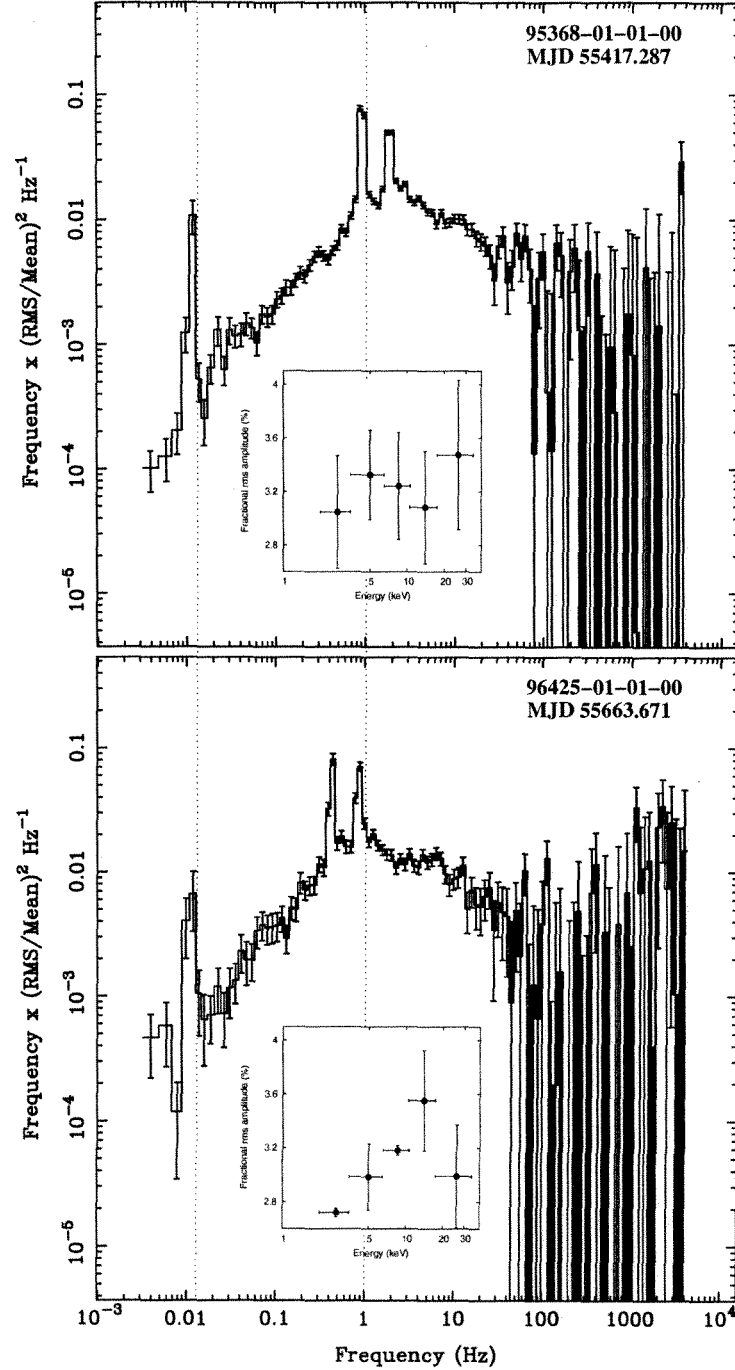


Fig. 5.— Power spectra of the two RXTE observations where we detect the mHz QPOs. The vertical dotted lines drawn at 0.0125 Hz and 1 Hz are shown to guide the eye. In the upper panel (2010 observation) the Type-C QPOs are at 0.919 ± 0.001 Hz and 1.852 ± 0.001 Hz while in the lower panel (2011 observation) they are at 0.424 ± 0.003 Hz and 0.856 ± 0.004 Hz. Their quality factors (Q) are 13.0 ± 0.5 , 10.0 ± 0.6 , 11 ± 2 and 9 ± 1 and their fractional rms amplitudes $11.9 \pm 0.2\%$, $9.4 \pm 0.2\%$, $10.7 \pm 0.4\%$, $10.9 \pm 0.5\%$, respectively. The inset panels show the fractional rms amplitude vs. energy for the 11 mHz QPOs.

for each PCU we calculate, in the same manner as for H1743–322, the colors of the Crab, which can be supposed to be constant. We then average the 16s Crab colors and intensity for each PCU for each day. For each PCU we divide the 16s color and intensity values obtained for H1743–322 by the corresponding average Crab values that are closest in time but in the same RXTE gain epoch. Then, we average the colors and intensity over all PCUs. Finally, we average the 16s colors per observation.

2.2. Timing analysis

To construct Leahy-normalized power spectra per observation we used data from the PCA’s Event, Good-Xenon and Single Bit modes. No background or deadtime corrections were made prior to the calculation of the power spectra. We subtracted a predicted dead-time modified Poisson noise spectrum estimated from the power at frequencies higher than 1500 Hz, where neither intrinsic noise nor QPOs are known to be present, using the method developed by Klein-Wolt (2004). The resulting power spectra were converted to squared fractional rms (van der Klis 1995).

We used 1-sec resolution PCA (2–60 keV) and Swift/XRT (0.5–10 keV) light curves to searched for periodicities on per orbit basis using Lomb-Scargle periodograms (Lomb 1976; Scargle 1982; Press et al. 1992).

3. Results

3.1. Search for mHz QPOs

We visually inspected each of the Lomb-Scargle periodograms and find clear evidences of mHz QPOs at ~ 0.011 Hz (~ 88 sec) in the two observations 95368-01-01-00 (MJD 55417.24, two orbits starting on August 9th, 2010 at 16:05 UT) and 96425-01-01-00 (MJD 55663.67, single orbit on April 12th, 2011 at 6:45 UT). The oscillations are also clearly visible in the light curves (see panels A-C in Figure 1). The quality factor Q is as high as ~ 100 in the 2010 observation, but also as low as ~ 10 in the 2011 observation. The average fractional rms amplitude in the 2–60 keV is 3.1 ± 0.4 %. In the 2010 observation the rms amplitude does not vary with energy, while in the 2011 observation it first increases and then shows evidence of a decrease. However, note that the increase is only moderate ($< 1\%$ rms), while other QPO variability generally shows a more substantial increase with energy (see, e.g., Casella et al. 2004).

We visually inspected each of the Lomb-Scargle periodograms and found no evidence of mHz QPOs in any of the Swift/XRT observations. We have no Swift–RXTE simultaneous observations when the mHz QPOs were detected. The closest Swift/XRT observation to the 2010 RXTE detection of mHz QPOs occurred approximately two days before and five days later while the closest observation to the 2011 RXTE detection occurred about 5 days later.

A Chandra/HETG observation was contemporaneous to that of RXTE observation 95368-01-01-00. We extracted events both from the zeroth (undispersed) and dispersed orders and found in both cases a clear QPO at ~ 11 mHz. In Figure 2 we show the dynamical power spectrum computed from the dispersed photons. The QPO frequency drifts upward with time and appears to be positively correlated with the intensity. The presence of the QPO signal in the zeroth order photons at a sky position consistent with the known position of H1743–322 confirms that the mHz QPO is intrinsic to this source, and not from a hitherto unidentified nearby source. A phase-resolved spectral analysis of these data is beyond the scope of this paper and will be reported elsewhere.

3.2. Outburst light curves and hardness-intensity diagrams

In Figure 3 we show the light curve of H1743–322. Nine outbursts are visible; not all equally well sampled. The detections of mHz QPOs correspond to observations at the beginning of the last two outbursts, i.e. of the 2010 and 2011 outbursts. In Figure 4 we show the hardness-intensity diagram (HID) for H1743–322. The last two outbursts show very similar tracks in the HID, and the mHz QPOs appear at a very similar hard color. However, note that an observation during the 2011 outburst shows no evidence of mHz QPOs, but shows very similar hard color and intensity as those of the 2010 observation in which we also detect mHz QPOs.

3.3. Full-frequency power-spectra

We calculated power spectra with RXTE data using 512s data segments for the two observations in which we found mHz QPOs. In Figure 5 we show the resulting power spectra, where the peak at about ~ 11 mHz is clearly visible in both cases. The power spectra also show the typical Type-C QPOs on top of strong ($\sim 30\%$) broad band noise. Although the frequency of the mHz QPOs is similar in both observations, the frequency of the Type-C QPOs differ by a factor of ~ 2 . We compared the overall power spectra produced from data from different phases of the ~ 11 mHz QPO, but found no significant changes, implying that

the mechanisms that produce the mHz QPOs and Type-C QPOs are probably independent.

4. Discussion

We report the discovery of quasi-periodic oscillations at ~ 11 mHz in two RXTE and one Chandra observation of the BHC H1743–322. In successive outbursts eight months apart we measure a QPO frequency that differs by less than ≈ 0.0015 (including the 60 ks duration of the *Chandra* observation, see Figure 2). The fractional rms amplitude of the mHz QPOs is consistent with constant at $\sim 3\%$ in the 2010 observation, but correlated with energy in the 2011 observation. The QPO is observed at the beginning of two different outbursts at similar hard color and intensity, suggestive of an accretion state dependence for the QPO. Although the *Chandra* data reveal that the QPO frequency is correlated with intensity on timescales of hours, this correlation probably changes in between outbursts, as we find the same frequency (within ≈ 0.0004 Hz) in observations separated by about 800 days and at source intensities different by ≈ 10 mCrab (this resembles the so called “parallel tracks” observed in the frequency vs. intensity diagrams of NS kHz QPOs, see, e.g., Méndez et al. 1999). Except for the 11 mHz QPOs, the RXTE power spectra of these two observations are typical of the low-hard state of BH LMXBs, showing Type-C QPOs on top of strong broad band noise. Given that (i) the power spectra characteristics does not change with mHz QPO phase and (ii) the frequency of the mHz QPOs is constant (within ≈ 0.0004 Hz) while the Type-C QPO frequency varies by a factor of about 2, we conclude that mechanisms that produce the mHz QPOs and Type C QPOs are probably independent.

The fact that the frequency of these new oscillations is fairly constant raises the question of whether they represent a characteristic frequency of a process not yet identified before. Several types of QPOs with frequencies in the mHz range have been reported in two BH systems and in some NS systems. Below we compare our results with those seen in other sources and discuss whether we can identify the 11 mHz QPOs with any of them based on the characteristics of the oscillations and the source state in which they occur.

Highly structured, high-amplitude variability has been seen in the BH systems GRS 1915+105 (e.g., Belloni et al. 2000) and IGR J17091–3624 (e.g., Altamirano et al. 2011). Some of these variations are known as “heartbeats” and are thought to be due to limit cycles of accretion and ejection in an unstable disk (e.g., Neilsen et al. 2011). These “heartbeat” QPOs are in the mHz range, occur only during the high-luminosity, soft-state of these two BH systems and, at least in the case of IGR J17091–3624, can have rms amplitudes as low as $\sim 3\%$ (e.g., Altamirano et al. 2011). For H1743–322 we only find the new mHz QPOs during the rise of the outburst (at $L_X < 3 \cdot 10^{37}$ ergs s $^{-1}$, e.g., Motta et al. 2010), when the spectrum of the

source is dominated by the hard component. GRS 1915+105 is thought to be very often at an Eddington or a super-Eddington luminosity (e.g., Done et al. 2004); this could also be the case of IGR J17091–3624 although the distance to this source is not yet known (see discussion in Altamirano et al. 2011). Given the major differences between source state and luminosity in GRS 1915+105 and IGR J17091–3624 as compared with H1743–322, we conclude that the mHz QPOs in H1743–322 most probably represent a different phenomenon than the “heartbeat” QPOs and the other highly-structured low-frequency variability seen in GRS 1915+105 and IGR J17091–3624.

QPOs with intensity-independent frequencies in the mHz range have been found in at least for 4 NS systems (Revnivtsev et al. 2001; Strohmayer & Smith 2011). The occurrence of these QPOs depends on source state, but are thought to be the signature of marginally stable burning of Helium on the NS surface (Heger et al. 2007). A similar QPO, but with an intensity-dependent frequency was also found in the 11 Hz X-ray pulsar IGR J17480–2446 in Terzan 5 (Linares et al. 2011). The fact that (i) the occurrence of these NS oscillations are intimately related with thermonuclear X-ray bursts, (ii) are thought to come from the NS surface and (iii) their spectrum is generally soft (Revnivtsev et al. 2001; Altamirano et al. 2008b), indicates that they are most probably a different phenomena from what we detect in H1743–322.

Wijnands (2004) reported a modulation at a ~ 1 Hz in the light curve of the accreting millisecond X-ray pulsar (AMXP) SAX J1808.4–3658. A similar type of QPO (Patruno et al. 2010) was found in the AMXP NGC 6440 X-2 (Altamirano et al. 2009). These QPOs have been seen at low luminosities (less than a few 10^{36} erg s $^{-1}$), at frequencies between 0.8 and 1.6 Hz and showing up to 100% fractional rms amplitudes (Patruno et al. 2009). The high rms amplitude of these oscillations, the fact that they have only been seen in AMXPs, and that their occurrence is most probably related to the onset of the propeller³ regime (Patruno et al. 2009) suggests that these ~ 1 Hz QPOs are not related to those we see in H1743–322.

A so called “1 Hz QPO” has been reported for (four) dipping NS systems (Jonker et al. 1999, 2000; Homan et al. 2003; Bhattacharyya et al. 2006). These QPOs appear to be different from the “zoo” of low-frequency features seen in the power spectra of NS systems. The fractional rms amplitude of these QPOs is approximately constant and energy independent during the persistent emission, dips and thermonuclear X-ray bursts. Although the QPO

³Regime in which the accretion flow onto the NS surface is suppressed when the keplerian velocity at the innermost region of the accretion disk is slower than the rotational velocity of the NS magnetosphere (Illarionov & Sunyaev 1975)

frequency has been seen to vary between 0.6 and 2.4 Hz in two of the sources (Jonker et al. 2000; Homan et al. 1999), the “1 Hz QPO” name stands for the fact that its frequency can be rather constant for long periods of time. It has been suggested that these QPOs are related only to high inclination sources from which we might be observing modulation effects of the material in the accretion stream onto the disk, or some kind of modulation produced at the disk edge (e.g., Jonker et al. 2000; Smale et al. 2001; van der Klis 2006, and references within). The fact that H1743–322 is thought to be a high inclination source (Homan et al. 2005), that the fractional rms amplitude of the mHz QPOs we find does not vary strongly with energy and that its frequency is stable, indicate that they might be related to the process that produces the so called “1 Hz QPO” in dipping NS systems. If true, this would be the first BH system showing such QPOs, raising the question of why the frequency of the QPO is between one and two orders of magnitude lower in H1743–322 than in the NS. One possibility is that the frequency range in which this QPO occurs scales with mass as $1/M_{BH}$ or that it depends on orbital period of the system, as H1743–322 is thought to have an orbital period longer than 10 hr (Jonker et al. 2010) while the NS systems have orbital periods shorter than 6 hr (e.g., Jonker et al. 1999, 2000; Homan et al. 2003). It is worth noting that the high inclination dipping BHC 4U 1630–47 shows QPOs as low as ~ 0.1 Hz, however, these QPOs are due to semi-regular short (~ 5 sec) dips (e.g., Dieters et al. 2000). Following Kuulkers et al. (1998) we produced colors using 1 sec light curves in different bands of the 2010 and 2011 observation of H1743–322. We do not observe any hardening (or any other variation) of the spectra as a function of QPO phase, implying that the 11 mHz QPOs are most probably not regular dips as seen in 4U 1630–47.

H1743–322 is well known for its radio jets (e.g., Steiner et al. 2011; Miller-Jones et al. 2012). Indeed, Markoff et al. (2005) have suggested that the hard state emission could be due to synchrotron self-Compton emission from the base of the jet, and Russell et al. (2010) have recently suggested that the jet mechanism might have dominated the X-ray variability in a portion of the hard state of the 2000 outburst of the BHC XTE J1550–556. The 11 mHz QPOs we find in H1743–322 appear to be different from most type of variability seen in other BH and NS systems, and so we speculate that they could be related to the jets seen in H1743–322. Unfortunately no radio measurements have been reported as yet for the 2010 and 2011 outbursts of H1743–322 (and the radio flux is known to change between outbursts, Miller-Jones et al. 2012) and to our knowledge no model yet predicts that the jet could sometimes modulate the X-ray flux at a characteristic frequency. Clearly more theoretical work is needed in this direction. In any case, remains unexplained why these low-frequency QPOs have not yet been identified in other BHs (probably a systematic search is needed) and why they have only been seen in the last two outbursts of H1743–322.

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